ANNEX Q

Methodology for Estimating CH_4 Emissions from Landfills

Landfill gas is a mixture of substances generated when bacteria decompose the organic materials contained in municipal solid waste (MSW). By volume, MSW landfill gas is about half methane and half carbon dioxide.[1] The amount and rate of methane generation depends upon the quantity and composition of the landfilled material, as well as the surrounding landfill environment.

Not all methane generated within a landfill is emitted to the atmosphere. If no measures are taken to extract the methane, a portion of it will oxidize as it travels through the top layer of the landfill cover. The portion of the methane that oxidizes turns primarily to carbon dioxide (CO_2). If the methane is extracted and either flared or utilized for energy, then that portion of the methane generated will also be oxidized to CO_2 during combustion. In general, landfill-related CO_2 emissions are of biogenic origin and primarily result from the decomposition, either aerobic or anaerobic, of organic matter such as food or yard wastes.[2]

To estimate the amount of methane produced in a landfill in a given year, information is needed on the type and quantity of waste in the landfill, as well as the landfill characteristics (e.g., size, aridity, waste density). However, this information is not available for all landfills in the United States. Consequently, a methodology to estimate methane emissions based on available landfill-specific data on waste in place (WIP) was developed.

From an analysis of the population of MSW landfills, the quantity of waste disposed in U.S. landfills was simulated in a landfill population model, which also modeled changes in landfill size over time. An EPA study of the methane generation properties of landfilled waste was then used in an emissions model to estimate methane generation. Based on organic content in industrial landfills, methane emissions from industrial landfills were assumed to be seven percent of the total methane generated from MSW at landfills. Total methane emissions were estimated by adding the methane from MSW and industrial landfills, subtracting the amount recovered and used for energy or flared, and subtracting the amount oxidized in the soil. The steps taken to estimate emissions from U.S. landfills for the years 1990 through 2001 are discussed in greater detail below.

Figure Q-1 presents the methane emissions process—from waste generation to emissions—in graphical format.

Step 1: Estimate Municipal Solid Waste Landfilled by Individual Landfill

First, a landfill survey was used to estimate the amount and distribution of landfilled waste in the United States (EPA 1988). The survey consisted of approximately 1,100 landfills representative of approximately 6,000 landfills that were active in the United States in 1986, and included information on annual waste acceptance, size, design capacity, open year, and closure year. The landfills selected in the survey varied by age, depth, regional distribution, and other factors.

Based on the results of this survey, a population model was developed to simulate the flow of landfilled waste from 1960 through the current year. For 1960 to 1990, the data from the landfill survey were extrapolated to other years using annual waste acceptance, design capacity, open year, and closure year. For 1991 to 2001, the model distributed estimates of total waste landfilled from BioCycle's *State of Garbage in America* report across the U.S. landfill population based on the same variables.[3] If landfills reached their design capacity, they were simulated to close. New landfills were simulated to open when a significant shortfall in disposal capacity was predicted. Simulated new landfills were assumed to be larger, on average, reflecting the trend toward fewer and more

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[1] Landfill gas also contains small amounts of nitrogen, oxygen, and hydrogen, less than 1 percent nonmethane volatile organic compounds (NMVOCs), and trace amounts of inorganic compounds.

[2] See Box 7-1 in the Waste chapter for additional background on how biogenic emissions of landfill CO_2 are addressed in the U.S. Inventory.

[3] Since the BioCycle survey does not include U.S. territories, waste generation from U.S. territories was estimated using population data for the U.S territories (U.S. Census Bureau 2000) and U.S. per capita waste generation (EPA 2002b).

centralized facilities. The analysis updated the landfill characteristics each year, calculating the profile of waste disposal over time.

Table Q-1 shows the BioCycle estimates of total waste landfilled each year from 1990 through 2000, adjusted for U.S. territories. Regression analysis was used to develop an estimate of waste landfilled in 2001, since BioCycle data were not yet available at the time this report was published.

Step 2: Estimate 30-Year Waste In Place by Landfill for Municipal Solid Waste Landfills

Methane is generated for approximately 30 years after waste is landfilled (EPA 1993). Consequently, each landfill's 30-year WIP was estimated in order to estimate methane generation in 2001.[4] For each landfill, this estimate was calculated as the sum of the MSW landfilled over the previous 30 years, as shown in the following equation:

$$waste\ in\ place\ (tons) = \sum_{t=1972}^{2001} waste\ landfilled\ (tons)$$

Closed landfills were included in this analysis, since they continue to generate methane after closure.

Step 3: Estimate Methane Generation at Municipal Solid Waste Landfills

Each landfill's WIP estimate was then converted to methane generation using the following emissions equations:

Small landfills (< 2 MMT WIP): CH_4 (m3/min) = 7.43 WIP (10^6 MT)

Large landfills (> 2 MMT WIP): CH_4 (m3/min) = 8.22 + 5.27 WIP (10^6 MT)

These equations are the result of a regression analysis performed by EPA of 85 large landfills in the United States (EPA 1993). Equations for small landfills were estimated by averaging the estimates of methane generation per megagram of WIP for each of the 85 large landfills. The study resulted in four emissions equations for each of the following landfill size and aridity combinations: small/arid, small non-arid, large/arid, and large/non-arid. Data on the percentage of U.S. landfills in arid versus non-arid locations were then used to develop the two weighted equations shown above.

These equations were incorporated into an emissions model that converted WIP for each landfill to methane generation. Total methane generation was then calculated as the sum of methane generation from all landfills, open and closed.

Step 4: Estimate Methane Generation at Industrial Landfills

Industrial landfills receive waste from factories, processing plants, and other manufacturing activities. Because no data were available on methane generation at industrial landfills, emissions from industrial landfills were assumed to equal seven percent of the total methane emitted from MSW landfills (EPA 1993). This estimate was based on the relative quantities and organic content of industrial waste compared to municipal waste at the time of the EPA study, as shown in the equations below (EPA 1993):

8.6 MMT organic waste in industrial landfills	÷	65% organic content of MSW	=	13.2 MMT of equivalent total MSW

13.2 MMT ÷ 190 MMT total MSW in MSW landfills = 7%

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[4] Other methods exist for estimating landfill methane emissions, such as the first order decay method. However, these methods require data that are not readily available for the U.S. landfill population. In particular, landfill-specific data on the waste composition and rate of methane generation are not available for the over 2,000 U.S. landfills. EPA believes that using landfill specific data on the waste-in-place provides a better approximation of methane generation than the use of national average coefficients for model parameters that are necessary to use other methods. Consequently, EPA uses the regression equations rather than other methods that are typically applied to evaluate methane generation.

Estimates of methane generation from industrial landfills are shown in Table Q-2.

Step 5: Estimate Methane Emissions Avoided

The estimate of methane emissions avoided (e.g., combusted) was based on landfill-specific data on flares and landfill gas-to-energy (LFGTE) projects.

Step 5a: Estimate Methane Emissions Avoided Through Flaring

The quantity of methane flared was based on data collected from flaring equipment vendors, including information on the quantity of flares, landfill gas flow rates, and year of installation (ICF 2002). To avoid double counting, flares associated with landfills that had an LFGTE project were excluded from the flaring analysis. The median landfill gas flow rate provided by vendors was used to estimate methane recovered from each remaining flare. However, several vendors provided information on the size of the flare rather than the landfill gas flow rate. To estimate a median flare rate for flares associated with these vendors, the size of the flare was matched with the size and corresponding flow rates provided by other vendors. Total methane recovered through flaring was estimated by summing the estimates of methane recovered by each flare for each year.

Step 5b: Estimate Methane Emissions Avoided Through Landfill Gas-to-Energy (LFGTE) Projects

The quantity of methane avoided due to LFGTE systems was estimated based on information in a database compiled by EPA's Landfill Methane Outreach Program (EPA 2002a). Using data on landfill gas flow and energy generation (i.e. MW capacity), the total direct methane emissions avoided due to the recovery and use of methane were estimated.

Step 5c: Reduce Methane Emissions Avoided Through Flaring

As mentioned in Step 5a, flares associated with LFGTE projects were excluded from the flare analysis. If EPA had comprehensive data on flares, each LFGTE project would have an identified flare because most LFGTE projects have flares. However, given that the flare data only covers approximately 50 to 75 percent of the flare population, an associated flare was not identified for all LFGTE projects. These LFGTE projects likely have flares, however EPA was unable to identify a flare due to one of two reasons: 1) inadequate identifier information in the flare data; or 2) the lack of the flare in the database. For those projects for which a flare was not identified due to inadequate information, EPA would be overestimating methane avoided as both the methane avoided from flaring and the LFGTE project would be counted. To avoid overestimating emissions avoided from flaring, EPA determined the methane avoided from LFGTE projects for which no flare was identified and reduced the flaring estimate by this quantity. This step likely results in an underestimate of methane avoided due to flaring. EPA took this approach to be conservative in the estimates of methane avoided.

Step 6: Estimate Methane Oxidation

A portion of the methane escaping from a landfill oxidizes to carbon dioxide in the top layer of the soil. The amount of oxidation depends upon the characteristics of the soil and the environment. For purposes of this analysis, it was assumed that ten percent of the methane produced, minus the amount of gas recovered for flaring or LFGTE projects, was oxidized in the soil (Liptay et al. 1998). This oxidation factor was applied to the methane generation estimates for both MSW and industrial landfills.

Step 7: Estimate Total Methane Emissions

Total methane emissions were calculated by adding emissions from MSW and industrial waste, and subtracting methane recovered and oxidized, as shown in Table Q-2.

Table Q-1: Municipal Solid Waste (MSW) Contributing to Methane Emissions (Tg unless otherwise noted)

Description	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Total MSW Generated[a]	269	258	268	281	296	299	300	312	343	350	374	370
Percent of MSW Landfilled[a]	77%	76%	72%	71%	67%	63%	62%	61%	61%	60%	61%	61%
Total MSW Landfilled	207	196	193	200	198	189	186	190	209	210	228	228
MSW Contributing to Emissions[b]	4,926	5,027	5,164	5,296	5,434	5,568	5,686	5,802	5,920	6,051	6,165	6,280

[a] Source: *BioCycle* (2001), adjusted for missing U.S. territories using U.S. Census Bureau (2000), and EPA (2002b). The data, originally reported in short tons, are converted to metric tons. Data shown for 1990 are not used in EPA analysis (see "step 1" above). Data shown for 2001 based on regression analysis using historical waste generation and population, as BioCycle data were not available at the time this report was published.

[b] The emissions model (EPA 1993) defines all waste that has been in place for less than 30 years as contributing to methane emissions.

Table Q-2: Methane Emissions from Landfills (Gg)

Activity	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
MSW Generation	**11,599**	**11,837**	**12,175**	**12,510**	**12,863**	**13,238**	**13,520**	**13,802**	**14,047**	**14,385**	**14,659**	**14,954**
Large Landfills	4,534	4,625	4,771	4,927	5,127	5,314	5,488	5,663	5,836	6,055	6,231	6,439
Medium Landfills	5,791	5,912	6,071	6,223	6,349	6,515	6,607	6,699	6,755	6,857	6,941	7,016
Small Landfills	1,273	1,300	1,332	1,360	1,387	1,409	1,425	1,440	1,456	1,474	1,487	1,499
Industrial Generation	**812**	**829**	**852**	**876**	**900**	**927**	**946**	**966**	**983**	**1,007**	**1,026**	**1,047**
Potential Emissions	**12,411**	**12,665**	**13,027**	**13,385**	**13,764**	**14,165**	**14,466**	**14,768**	**15,030**	**15,392**	**15,685**	**16,001**
Emissions Avoided	**(1,190)**	**(1,460)**	**(1,667)**	**(1,916)**	**(2,283)**	**(2,732)**	**(3,244)**	**(3,790)**	**(4,320)**	**(4,613)**	**(4,798)**	**(5,263)**
Landfill Gas-to-Energy	(732)	(772)	(826)	(892)	(1,028)	(1,064)	(1,220)	(1,452)	(1,752)	(2,002)	(2,187)	(2,396)
Flare	(458)	(687)	(841)	(1,023)	(1,255)	(1,668)	(2,024)	(2,338)	(2,568)	(2,611)	(2,611)	(2,867)
Oxidation at MSW Landfills	**(1,041)**	**(1,038)**	**(1,051)**	**(1,059)**	**(1,058)**	**(1,051)**	**(1,028)**	**(1,001)**	**(973)**	**(977)**	**(986)**	**(969)**
Oxidation at Industrial Landfills	**(81)**	**(83)**	**(85)**	**(88)**	**(90)**	**(93)**	**(95)**	**(97)**	**(98)**	**(101)**	**(103)**	**(105)**
Net Emissions	**10,099**	**10,085**	**10,224**	**10,323**	**10,333**	**10,290**	**10,100**	**9,880**	**9,639**	**9,701**	**9,798**	**9,663**

Note: Totals may not sum due to independent rounding.

Note: MSW generation in Table Q-2 represents emissions before oxidation. In other tables throughout the text, MSW generation estimates account for oxidation.

( ) denotes a negative value

Figure Q-1: Methane Emissions Resulting from Landfilling Municipal and Industrial Waste

*Seven percent represents the relative methane generation at MSW landfills versus industrial landfills, and is based on a comparative analysis of MSW and industrial waste (see "step 4" above). Consequently, the value for methane generated at industrial landfills is not subtracted from the value for methane generation at MSW landfills.

[a] BioCycle

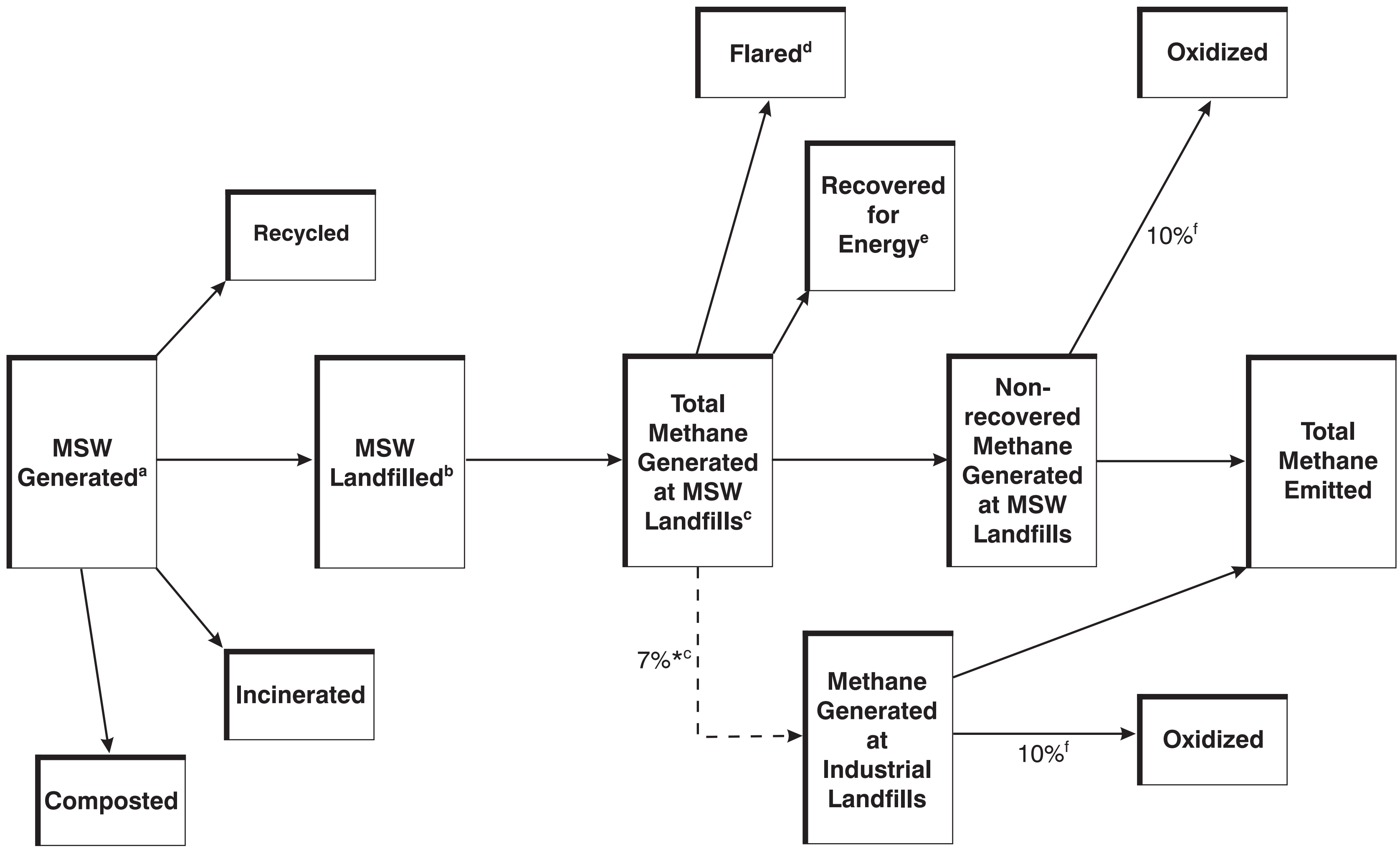
[b] 1961 through 1990 based on EPA 1988; 1991 through 2001 based on BioCycle

[c] EPA 1993

[d] ICF Consulting 2002

[e] EPA 2002a

[f] Liptay et al. 1998



MSW Generated[a]
Recycled
MSW Landfilled[b]
Incinerated
Composted
Total Methane Generated at MSW Landfills[c]
Flared[d]
Recovered for Energy[e]
7%*[c]
Methane Generated at Industrial Landfills
Non-recovered Methane Generated at MSW Landfills
Oxidized
10%[f]
Total Methane Emitted
Oxidized
10%[f]